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Single Langmuir Probe Measurements in an Unbalanced Magnetron Sputtering System

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Abstract

The measurements of plasma parameters from inside a plasma boundary give more accurate results. Current-voltage (*I-V*) characteristics were obtained from plasma measurements in an unbalanced magnetron sputtering system using a Langmuir probing technique which collects the measured data from a biased probe inserted inside the plasma. These *I-V* characteristics were used to analyze the plasma parameters such as plasma potential, electron temperature and electron density during sputter deposition of Ti thin films. The spatial distribution of the plasma was measured at different distances from the cathode target, such as 6, 8 and 10 cm. At 8 cm distance from the cathode target, the plasma parameters were investigated at different distances along the target radius such as 1, 2 and 3 cm. The plasma parameters of sputtered Ti thin films were investigated at different deposition conditions. The effect of the position of the single Langmuir probe and deposition conditions on the plasma parameters was studied. The plasma potential was found in the range of 4.4-5.0 V. An electron temperature was found in the range of 0.8-2.2 eV, corresponding to a plasma density in the range of 5.5×10^{17}-1.2×10^{18} m^{-3}. The plasma parameters strongly depended on the position of the probe and deposition conditions.

Keywords: Plasma parameters; electron temperature; plasma density; plasma potential

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1. Introduction

Generally, the properties of titanium (Ti) thin films that are deposited on a substrate by unbalanced direct current (DC) magnetron sputtering system depend on substrate position and deposition conditions. Argon (Ar) gas is widely used in sputtering applications, including the deposition of Ti thin films. The plasma parameters during deposition of Ti thin films, therefore, should be known in order to predict films properties. There are several methods to measure the plasma parameters, such as microwave interferometry [1], ion energy analysis [2, 3] and electrical probe diagnostics [4]. Electric probes are indispensable diagnostic tools for plasma research, especially in the areas of low gas pressure and cold plasmas [4, 5]. An advantage of these probes is its ability to provide local measurements of plasma parameters. The measured values of plasma parameters will be more accurate if the measurement is made inside the plasma boundary. There are several types of electric probe, for example; single Langmuir probes, double Langmuir probes and triple Langmuir probes. Single Langmuir probe has been used extensively due to their simplicity. This probe consists of a bare wire or metal disk which is inserted inside the plasma, and which is biased with a voltage V whilst measuring the current, I. These I-V characteristics are used to analyze the plasma parameters such as plasma potential (V_p), electron temperature (T_e) and electron density (n_e) [1,6-7]. These parameters relate to the external parameters of the plasma system, for example; gas pressure, gas flow rate and dissipated power. Control of the external parameters in the plasma system, therefore, can lead to control of the plasma parameters, and hence to the film properties. In this paper, the results of plasma parameters of sputtered Ti thin films in unbalanced magnetron sputtering were determined by single Langmuir probe measurements.

2. Experimental Setup

The schematic diagram of an unbalanced DC magnetron sputtering system is shown in Fig. 1. The reactor chamber was made of stainless steel in a cylindrical form 31 cm in diameter. A 99.97% purity Ti target with 7.6 cm diameter was attached to the cathode which was connected to a high-power DC generator. 99.999% purity Ar gas was used as the sputtering gas. The vacuum system consisted of a diffusion pump backed by a rotary pump with a typical base pressure of 5.5×10^{-5} mbar. The pressure of the system was measured by a cold cathode gauge (IKR 50) and a Pirani gauge (TPR010) mounted at a port on the side flange of the chamber. During plasma operation, Ar gas was entered the chamber via a mass flow controller (MKS type 247D). The total pressure of Ar gas was used at 5×10^{-3} mbar for a flow rate of 5 sccm. In this work, the plasma source was powered by a DC power generator at various sputtering currents, such as 500,750 and 1,000 mA.

The single Langmuir probe used in this experiment was made of tungsten wire and had a radius of 0.05 cm. The length of the tip exposed in the plasma was ~0.3 cm. The part of the tungsten wire which is not exposed to the plasma was encapsulated in a glass tube. A variable voltage was supplied to this probe in the range -30 V to +30 V, and the I-V characteristics were measured. The plasma properties were measured at different distances from the cathode target, such as 6, 8 and 10 cm. At 8 cm distance from the cathode target, the plasma parameters were investigated at different distances along the target radius such as 1, 2 and 3 cm. The effect of the position of the Langmuir probe and deposition conditions on the plasma parameters was studied.

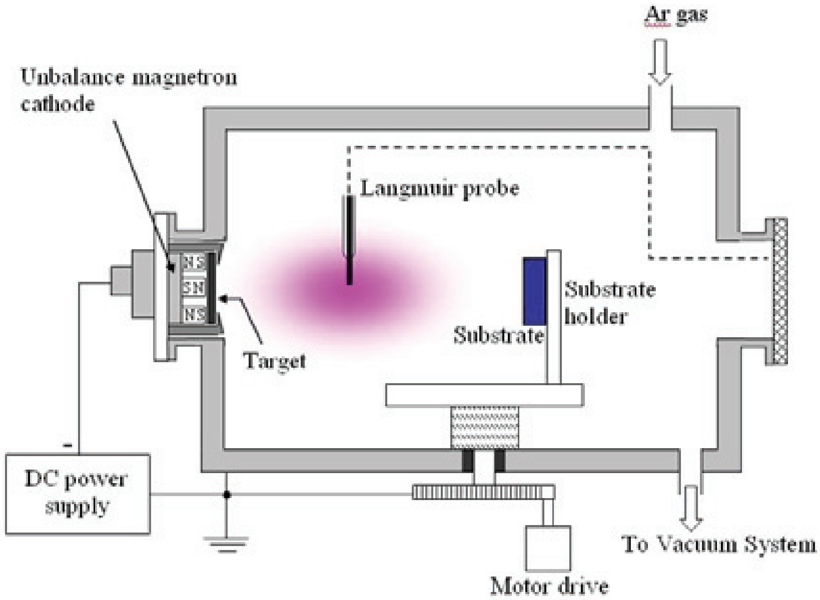

Fig. 1. Schematic diagram of an unbalanced DC magnetron sputtering system

3. Results and Discussion

Generally, the *I-V* characteristics can divide into three regions; (1) ion-current saturation region (I_{is}) (2) transition region and (3) electron-current saturation region (I_{es}). The I_{is} region shows that the probe current is mainly due to positive ion being attracted to the probe. The transition region shows that there is electron diffusion to the probe. The current varies exponentially with the probe voltage until the voltage equals the plasma potential (V_p). The I_{es} region occurs when the probe current is mainly due to electrons being attracted to the probe.

In this work, the *I-V* characteristics showed clearly two regions, I_{is} and the transition region. The I_{es} region cannot be distinguished because the highest voltage used +30 V was too small to completely repel all the positive ions. However, all *I-V* characteristics in this work were sufficiently well defined to allow plasma parameters to be derived from them. The transition region was chosen and fitted to derive the values of T_e and V_p. An example of an *I-V* characteristic obtained directly from the single Langmuir probe is shown in fig. 2(a).

Electron current has negligible distribution in the ion saturation region. This region was fitted to be a linear, which is extrapolated to obtain the ion current. The electron current was obtained by subtracting out the ion current from the plasma current. The T_e can be determined from the slope of a plot of logarithm of the electron current versus the probe potential, as shown in Fig. 2(b). This is based on the relation [1, 7, 8]:

$$\frac{d\left|\ln I_e\right|}{dV} = \frac{1}{T_e} \tag{1}$$

where I_e is the electron current, V is the probe potential and T_e is the electron temperature.

The T_e result versus distance from the cathode target and distance along the target radius are shown in Figs. 3(a) and 3(b), respectively. These figures show that the T_e was in the range 0.8-2.2 eV, depending upon the distance from the cathode target, distance along the target radius and sputtering current. At constant sputtering current, T_e decreased with increasing distance from the cathode target and decreased with increasing of distance along the target radius. At constant distance from the cathode target and distance along the target radius, the cathode targets that were powered at 1,000 mA sputtering current had a lower T_e value than the cathode targets that were powered at 500 mA.

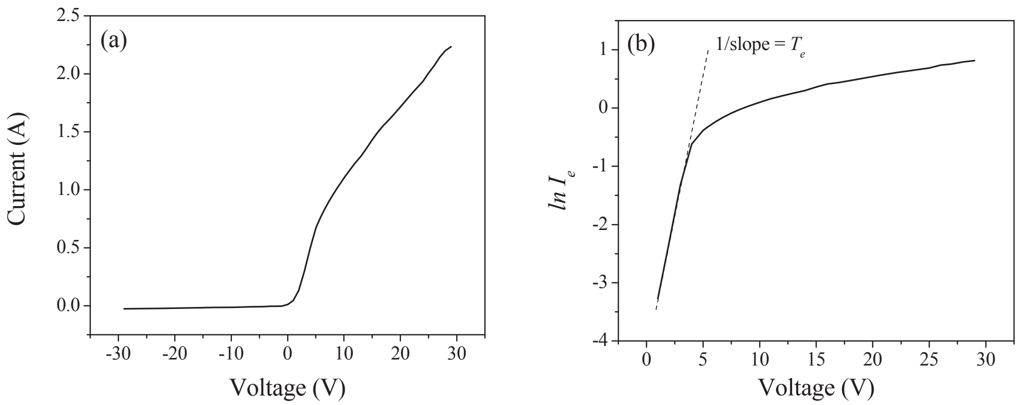

Fig. 2. A plot of (a) I-V characteristic; (b) logarithm of the electron current versus the probe potential

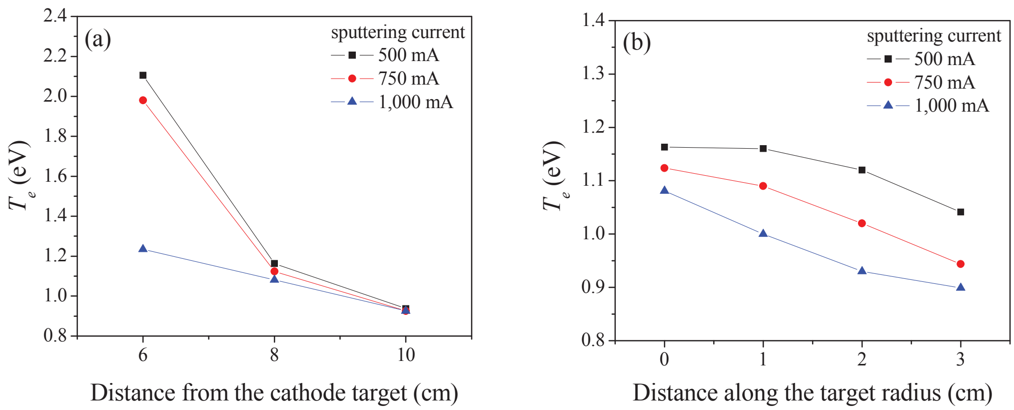

Fig. 3. Plots of T_e for different sputtering currents (a) at 6, 8 and 10 cm distance from the cathode target (b) at 0, 1, 2 and 3 cm along the target radius for an equal cathode target distance of 8 cm

In quasi-neutral non-equilibrium plasma, the n_e can be determined from equation [1, 7-8]:

$$n_e = \frac{1}{0.6es}\sqrt{\frac{M_i}{kT_e}} \cdot I_{is} \qquad (2)$$

where e is the charge of electron, s is the area of the exposed probe surface, M_i is the ion mass of the gaseous ion, k is the Boltzmann's constant and I_{is} is the ion saturation current.

The n_e result versus distance from the cathode target and distance along the target radius are shown in Figs. 4(a) and 4(b), respectively. These figures show that n_e was in the range 5.5×10^{17}-1.2×10^{18} m^{-3}, depending upon the distance from the cathode target, distance along the target radius and sputtering current. At constant sputtering current, n_e increased with increasing distance from the cathode target and increased with increasing distance along the target radius. At constant distance from the cathode target and distance along the target radius, the cathode targets that were powered at 1,000 mA sputtering current had a higher n_e value than the cathode targets that were powered at 500 mA.

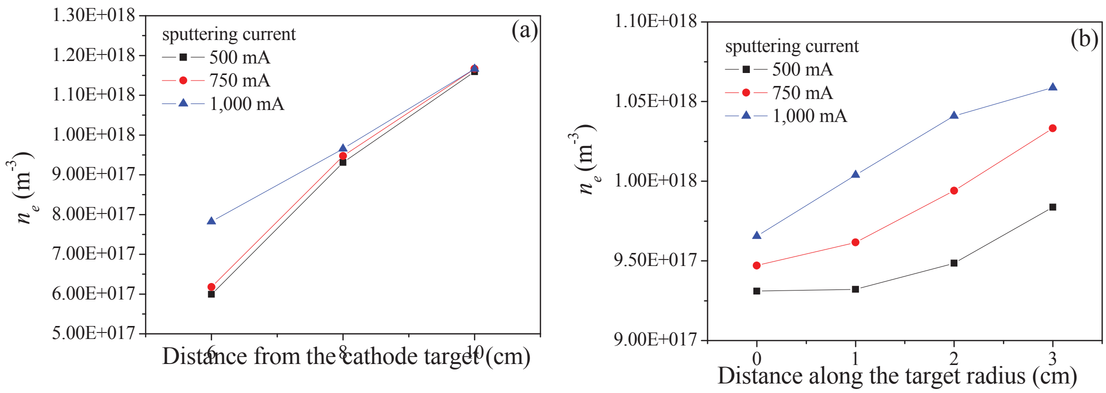

Fig. 4. Plots of n_e for different sputtering currents (a) at 6, 8 and 10 cm distance from the cathode target (b) at 0, 1, 2 and 3 cm along the target radius for an equal cathode target distance of 8 cm

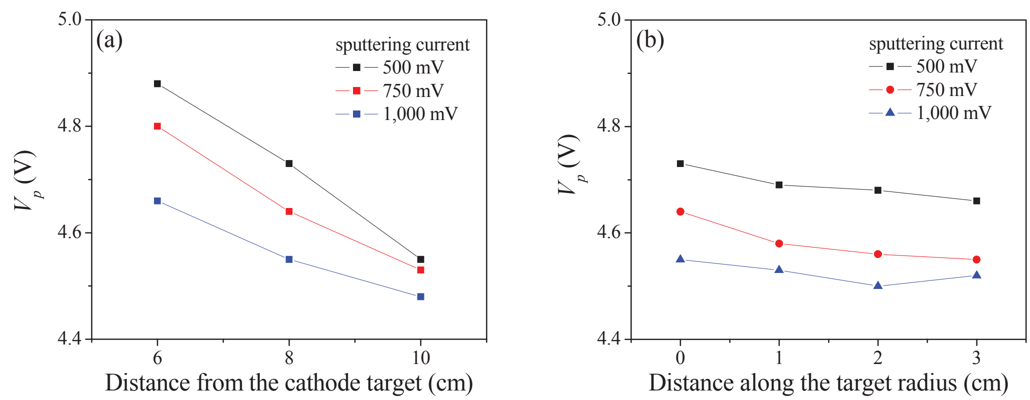

Fig. 5. Plots of V_p for different sputtering currents (a) at 6, 8 and 10 cm distance from the cathode target (b) at 0, 1, 2 and 3 cm along the target radius for an equal cathode target distance of 8 cm

In Fig. 5, V_p values are about 4.4 V - 5.0 V, depending upon the distance from the cathode target, distance along the target radius and sputtering current. At constant sputtering current, V_p decreased with increasing distance from the cathode target and decreased with increasing distance along the target radius.

At constant distance from the cathode target and distance along the target radius, the cathode targets that were powered at 1,000 mA sputtering current had a lower V_p value than the cathode targets that were powered at 500 mA.

At constant sputtering current, T_e and V_p were found to decrease but n_e was found to increase with increasing distance from the cathode target. This is because at shorter distance from the cathode target the electrons had higher average kinetic energy, because they had not lost much energy due to collisions with Ar atoms. With increasing distance from the cathode, the electrons have more collisions and lose more kinetic energy, decreasing T_e, but some collisions result in ionising Ar producing more electrons, hence increasing n_e. The V_p was always positive. This means that both ions and electrons will diffuse from the plasma where a higher density exists. This V_p was found to be higher at shorter distance from the cathode target due to longer average mean-free-path of electrons and lower collision frequency between electrons and particles. These results are similar to results in other reports [9-12].

T_e and V_p were found decrease with distance along the target radius but n_e was found increase. This is because the electrons had higher average kinetic energy of electrons at the center axis of the cathode target, making the argon plasma have higher T_e and V_p than at longer distances. These decreases in the T_e and V_p will be correlated to the increase in the n_e.

At constant distance from the cathode target and distance along the target radius, T_e and V_p were found decrease but the n_e was found increase with increasing sputtering current. This is because the amount of ions and electrons increased at higher sputtering current, making the argon plasma has more n_e. This increased density decreases the average mean-free-path of electrons, but increases the collision frequency between electrons and particles and lowers average kinetic energy. Thus, the T_e and V_p decreased at higher sputtering currents. These results are similar to results in other reports [9, 10].

4. Conclusion

Our results indicate that the V_p was found to be in the range of 4.4-5.0 V. The T_e was found in the range of 0.8-2.2 eV, corresponding to n_e in the range of 5.5×10^{17}-1.2×10^{18} m^{-3}. At constant sputtering current, the T_e and V_p decreased both with increasing distance from the cathode target and with increasing distance along the target radius, while the n_e increased both with increasing distance from the cathode target and with increasing distance along the target radius. At constant distance from the cathode target and distance along the target radius, the T_e and V_p decreased with increasing sputtering current, while n_e increased with increasing sputtering current. Therefore, the measured plasma parameters strongly depended on the position of single Langmuir probe and deposition conditions.

Acknowledgements

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